

اصول مهندسی مکانیک

# BASICS OF MECHANICAL ENGINEERING:

ادغام کردن و یکپارچه کردن

علم

فناوری

INTEGRATING SCIENCE, TECHNOLOGY  
AND COMMON SENSE

انفکاس کردن درونی افراد از تجربیات قبلی بر سر تفسیر تجربیات جدید، ادراک صحیح و فنایاری

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# Foreword

If you're reading this book, you're probably already enrolled in an introductory university course in Mechanical Engineering. The primary goals of this textbook are, to provide you, the student, with:

1. An understanding of what Mechanical Engineering is and to a lesser extent what it is not
2. Some useful tools that will stay with you throughout your engineering education and career
3. A brief but significant introduction to some of the major topics of Mechanical Engineering and enough understanding of these topics so that you can relate them to each other
4. A sense of common sense

The challenge is to accomplish these objectives without overwhelming you so much that you won't be able to retain the most important concepts.

In regards to item 2 above, I remember nothing about some of my university courses, even in cases where I still use the information I learned therein. In others I remember "factoids" that I still use. One goal of this textbook is to provide you with a set of useful factoids so that even if you don't remember any specific words or figures from this text, and don't even remember where you learned these factoids, you still retain them and apply them when appropriate.

In regards to item 3 above, in particular the relationships between topics, this is one area where I feel engineering faculty (myself included) do not do a very good job. Time and again, I find that students learn something in class A, and this information is used with different terminology or in a different context in class B, but the students don't realize they already know the material and can exploit that knowledge. As the old saying goes, "We get too soon old and too late smart..." Everyone says to themselves several times during their education, "Oh... that's so easy... why didn't the book [or instructor] just say it that way..." I hope this text will help you to get smarter sooner and older later.

A final and less tangible purpose of this text (item 4 above) is to try to instill you with a sense of common sense. Over my 33 years of teaching at the university level, I have found that students have become more technically skilled and well-rounded but have less ability to think and figure out things for themselves. I attribute this in large part to the fact that when I was a teenager, cars were relatively simple and my friends and I spent hours working on them. When our cars weren't broken, we would sabotage (nowadays "hack" might be a more descriptive term) each other's cars. The best hacks were those that were difficult to diagnose, but trivial to fix once you figured out what was wrong. We learned a lot of common sense working on cars. Today, with electronic controls, cars are very difficult to work on or hack. Even with regards to electronics, today the usual solution to a broken device is to throw it away and buy a newer device, since the old one is probably nearly obsolete by the time it breaks. Of course, common sense *per se* is probably not teachable, but a sense of common sense, that is, to know when it is needed and how to apply it, might be teachable. If I may be allowed an modest moment in this textbook, I would like to give an anecdote about my son Peter. When he was not quite 3 years old, like most kids his age had a pair of shoes with lights (actually light-emitting diodes or LEDs) that flash as you walk. These shoes work for a few months until the heel switch fails (usually in the closed position) so that the LEDs stay on continuously for a day or two until the battery goes dead. One morning he noticed that the LEDs in one of his shoes were on continuously. He had a puzzled look on his face but said nothing. Instead, he went to look for his other shoe, and after rooting around a bit, found it. He then picked it up, hit it against

something and the LEDs flashed as they were supposed to. He then said, holding up the good shoe, "this shoe - fixed... [then pointing at the other shoe] that shoe - broken!" I immediately thought, "I wish all my students had that much common sense..." In my personal experience, about half of engineering is common sense as opposed to specific, technical knowledge that needs to be learned from coursework. Thus, to the extent that common sense can be taught, a final goal of this text is to try to instill this sense of when common sense is needed and even more importantly how to integrate it with technical knowledge. The most employable and promotable engineering graduates are the most flexible ones, i.e. those that take the attitude, "I think I can handle that" rather than "I can't handle that since no one taught me that specific knowledge." Students will find at some point in their career, and probably in their very first job, that *plans and needs change rapidly* due to testing failures, new demands from the customer, other engineers leaving the company, etc.

In most engineering programs, *retention* of incoming first-year students is an important issue; at many universities, less than half of first-year engineering students finish an engineering degree. Of course, not every incoming student who chooses engineering as his/her major should stay in engineering, nor should every student who lacks confidence in the subject drop out, but in all cases it is important that incoming students receive a good enough introduction to the subject that they make an informed, intelligent choice about whether he/she should continue in engineering.

Along the lines of retaining first-year students in engineering, I would like to give an anecdote. At Princeton University, in one of my first years of teaching, a student in my thermodynamics class came to my office, almost in tears, after the first midterm. She did fairly poorly on the exam, and she asked me if I thought she belonged in Engineering. (At Princeton thermodynamics was one of the first engineering courses that students took). What was particularly distressing to her was that her fellow students had a much easier time learning the material than she did. She came from a family of artists, musicians and dancers and got little support or encouragement from home for her engineering studies. While she had some of the artistic side in her blood, she said that her real love was engineering, but she wondered was it a lost cause for her? I told her that I didn't really know whether she should be an engineer, but I would do my best to make sure that she had a good enough experience in engineering that she could make an informed choice from a comfortable position, rather than a decision made under the cloud of fear-of failure. With only a little encouragement from me, she did better and better on each subsequent exam and wound up receiving a very respectable grade in the class. She went on to graduate from Princeton with honors and earn a Ph.D. in engineering from a major Midwestern university. I still consider her one of my most important successes in teaching. Thus, a goal of this text is (along with the instructor, teaching assistants, fellow students, and infrastructure) is to provide a positive first experience in engineering.

There are also many topics that should be (and in some instructors' views, *must* be) covered in an introductory engineering textbook but are not covered here because the overriding desire to keep the book's material manageable within the limits of a one-semester course:

- |    |                           |                            |         |
|----|---------------------------|----------------------------|---------|
| 1. | History of engineering    | B.Sc. Bachelor of Science  | respect |
| 2. | Philosophy of engineering | M.Sc. Master               | expect  |
| 3. | Engineering ethics        | Ph.D. Philosophy of Doctor | except  |
|    |                           |                            | accept  |
|    |                           |                            | aspect  |

Finally, I offer a few suggestions for faculty using this book:

1. *Projects.* I assign small, hands-on design projects for the students, examples of which are given in Appendix A.
2. *Demonstrations.* Include simple demonstrations of engineering systems – thermoelectrics, piston-type internal combustion engines, gas turbine engines, transmissions, ...

3. *Computer graphics.* At USC, the introductory Mechanical Engineering course is taught in conjunction with a computer graphics laboratory where an industry-standard software package is used.

# Nomenclature

نورث

abbreviation sheet

Symbol	Meaning	SI units and/or value
A	Area	m <sup>2</sup>
BTU	British Thermal Unit	1 BTU = 1055 J
C <sub>D</sub>	Drag coefficient	---
C <sub>L</sub>	Lift coefficient	---
C <sub>p</sub>	Specific heat at constant pressure	J/kgK
C <sub>v</sub>	Specific heat at constant volume	J/kgK
c	Sound speed	m/s
COP	Coefficient Of Performance	---
d	Diameter	m (meters)
E	Energy	J (Joules)
E	Elastic modulus	N/m <sup>2</sup>
e	Internal energy per unit mass	J/kg
F	Force	N (Newtons)
f	Friction factor (for pipe flow)	---
g	Acceleration of gravity	m/s <sup>2</sup> (earth gravity = 9.81)
g <sub>c</sub>	USCS units conversion factor	32.174 lbf ft/ lbf sec <sup>2</sup> = 1
h	Convective heat transfer coefficient	W/m <sup>2</sup> K
I	Area moment of inertia	m <sup>4</sup>
I	Electric current	amps
k	Boltzmann's constant	1.380622 x 10 <sup>-23</sup> J/K
k	Thermal conductivity	W/mK
L	Length	m
M	Molecular Mass	kg/mole
M	Moment of force	N m (Newtons x meters)
M	Mach number	---
m	Mass	kg
$\dot{m}$	Mass flow rate	kg/s
n	Number of moles	---
N <sub>A</sub>	Avogadro's number (6.0221415 x 10 <sup>23</sup> )	---
P	Pressure	N/m <sup>2</sup>
P	Point-load force	N
Q	Heat transfer	J
q	Heat transfer rate	W (Watts)
R	Universal gas constant	8.314 J/mole K
R	Mass-based gas constant = R/M	J/kg K
R	Electrical resistance	ohms
Re	Reynolds number	---
r	Radius	m
S	Entropy	J/K
T	Temperature	K
T	Tension (in a rope or cable)	N

t	Time	s (seconds)
U	Internal energy	J
u	Internal energy per unit mass	J/kg
V	Volume	m <sup>3</sup>
V	Voltage	Volts
V	Shear force	N
v	Velocity	m/s
W	Weight	N (Newtons)
W	Work	J
w	Loading (e.g. on a beam)	N/m
Z	Thermoelectric figure of merit	1/K
z	elevation	m
$\alpha$	Thermal diffusivity	m <sup>2</sup> /s
$\gamma$	Gas specific heat ratio	---
$\eta$	Efficiency	---
$\varepsilon$	Strain	---
$\varepsilon$	Roughness factor (for pipe flow)	---
$\mu$	Coefficient of friction	---
$\mu$	Dynamic viscosity	kg/m s
$\theta$	Angle	---
$\nu$	Kinematic viscosity = $\mu/\rho$	m <sup>2</sup> /s
$\nu$	Poisson's ratio	---
$\rho$	Density	kg/m <sup>3</sup>
$\rho$	Electrical resistivity	ohm m
$\sigma$	Normal stress	N/m <sup>2</sup>
$\sigma$	Stefan-Boltzmann constant	$5.67 \times 10^{-8} \text{ W/m}^2\text{K}^4$
$\sigma$	Standard deviation	[Same units as sample set]
$\tau$	Shear stress	N/m <sup>2</sup>
$\tau$	Thickness (e.g. of a pipe wall)	m

# Units conversions

سہولت کار

Base units			
Type	SI unit	USCS unit	Other conversions
Length	meter (m)	3.281 foot (ft) = 1 m	1 m = 100 centimeters (cm) = 1000 millimeters (mm) = 39.37 inches (in) 1 kilometer (km) = 1000 m 1 mile (mi) = 5280 ft
Mass	kilogram (kg)	2.205 pounds mass (lbm) = 1 kg	1000 grams (g) = 1 kg 1 slug = 32.174 lbm
Time	second (s)	s	1 minute (min) = 60 s 1 hour (hr) = 60 min
Charge	coulomb (coul)	coul	1 coul = charge on $6.241506 \times 10^{18}$ electrons
Derived units			
Type	SI unit	USCS unit	Other conversions
Area (length <sup>2</sup> )	m <sup>2</sup>	10.76 ft <sup>2</sup> = 1 m <sup>2</sup>	1 acre = 43,560 ft <sup>2</sup> 640 acres = 1 mi <sup>2</sup> 1 hectare = 10,000 m <sup>2</sup> = 2.471 acre
Volume (length <sup>3</sup> )	m <sup>3</sup>	35.32 ft <sup>3</sup> = 1 m <sup>3</sup>	1 ft <sup>3</sup> = 7.48 gallons (gal) = 28,317 cm <sup>3</sup> (ml, cc) 1 m <sup>3</sup> = 264.2 gal 1 liter = 0.001 m <sup>3</sup> = 1000 cm <sup>3</sup> = 61.02 in <sup>3</sup>
Velocity (length/time)	m/s	3.281 ft/s = 1 m/s	60 mi/hr = 88 ft/s
Acceleration (length/time <sup>2</sup> )	m/s <sup>2</sup>	3.281 ft/s <sup>2</sup> = 1 m/s <sup>2</sup>	1 g (standard earth gravity) = 9.806 m/s <sup>2</sup> = 32.174 ft/s <sup>2</sup>
Force = $\frac{\text{mass} \times \text{length}}{\text{time}^2}$	1 Newton (N) = 1 kg m/s <sup>2</sup>	1 pound force (lbf) = 4.448 N	1 dyne = 1 g cm/s <sup>2</sup> = 10 <sup>-5</sup> N
Energy = $\frac{\text{mass} \times \text{length}^2}{\text{time}^2}$	1 Joule (J) = 1 kg m <sup>2</sup> /s <sup>2</sup> = 1 N m	1 J = 0.7376 (ft lbf) (foot-pound)	1 British Thermal Unit (BTU) = 1055 J = 778 ft lbf 1 calorie (cal) = 4.184 J 1 diet calorie = 1000 cal 1 erg = 1 g cm <sup>2</sup> /s <sup>2</sup> = 10 <sup>-7</sup> J
Power = $\frac{\text{mass} \times \text{length}^2}{\text{time}^3}$	1 Watt (W) = 1 kg m <sup>2</sup> /s <sup>3</sup> = 1 N m/s	1 horsepower (hp) = 746 W	1 hp = 550 ft lbf/s
Pressure = force/length <sup>2</sup>	1 Pascal (Pa) = 1 N/m <sup>2</sup> = 1 kg/m s <sup>2</sup>	1 lbf/in <sup>2</sup> = 6899 Pa	1 standard atmosphere (atm) = 101325 Pa = 14.696 lbf/in <sup>2</sup> 1 bar = 10 <sup>5</sup> Pa

Type	SI unit	USCS unit	Other conversions
Temperature	Kelvin (K)	1.8 Rankine (R) = 1 K	See notes below
Heat capacity = Energy mass × temperature	1 J /kg K = 1 J/kg°C	1 BTU/lbm°F = 1 BTU/lbmR = 1 cal/g°C	(Note: that's not a misprint, the conversion factor between BTU/lbm°F and cal/g°C is exactly 1)
Current = charge/time	1 Ampere (A or amp) = 1 coul/s	n/a	1 milliamp (mA) = 0.001 A
Voltage = energy/charge	1 Volt (V) = 1 J/coul	n/a	n/a
Capacitance = coul/Volt	1 Farad (f) = 1 coul/Volt = 1 coul <sup>2</sup> /J	n/a	1 microfarad (μf) = 10 <sup>-6</sup> f 1 picofarad (pf) = 10 <sup>-12</sup> f
Inductance = Volt / (amp/s)	1 Henry (H) = 1 J s <sup>2</sup> /coul <sup>2</sup>	n/a	1 millihenry (mH) = 0.001 H
Resistance = Volt/amp	1 Ohm (Ω) = 1 Volt/amp = 1 J s/coul <sup>2</sup>	n/a	n/a

### Temperature conversion formulae:

Kelvins (K, not °K) is the absolute temperature scale in SI units.

Rankines (R, not °R) is the absolute temperature scale in USCS units.

$$T \text{ (in units of } ^\circ\text{F)} = T \text{ (in units of R)} - 459.67$$

$$T \text{ (in units of } ^\circ\text{C)} = T \text{ (in units of K)} - 273.15$$

$$T \text{ (in units of } ^\circ\text{C)} = [T \text{ (in units of } ^\circ\text{F)} - 32]/1.8$$

$$T \text{ (in units of } ^\circ\text{F)} = 1.8[T \text{ (in units of } ^\circ\text{C)}] + 32$$

$$1 \text{ K of temperature change} = 1^\circ\text{C of temperature change}$$

$$= 1.8^\circ\text{F of temperature change} = 1.8 \text{ R of temperature change}$$

### Revolution conversion formulae:

$$1 \text{ revolution} = 2\pi \text{ radians} = 360 \text{ degrees}$$

**Ideal gas law** - note that there are many “flavors” of the ideal gas law:

$$PV = n\mathfrak{R}T$$

$$PV = mRT$$

$$Pv = \mathfrak{R}T$$

**P = ρRT** – most useful form for engineering purposes; more useful to work with mass than moles, because moles are not conserved in chemical reactions!

P = pressure (N/m<sup>2</sup>); V = volume (m<sup>3</sup>); n = number of moles of gas

℞ = universal gas constant (8.314 J/moleK); T = temperature (K)

m = mass of gas (kg); R = mass-specific gas constant = ℞/M

M = gas molecular mass (kg/mole); v = V/m = specific volume (m<sup>3</sup>/kg)

ρ = 1/v = density (kg/m<sup>3</sup>)

# Chapter 1. What is Mechanical Engineering?

"The journey of a thousand miles begins with a single step."

- Lao Tzu

## تعريف Definition of Mechanical Engineering

My personal definition of Mechanical Engineering is

If it needs engineering but it doesn't involve electrons, chemical reactions, arrangement of molecules, life forms, isn't a structure (building/bridge/dam) and doesn't fly, a mechanical engineer will take care of it... but

if it does involve electrons, chemical reactions, arrangement of molecules, life forms, is a structure or does fly, mechanical engineers may handle it anyway

Although every engineering faculty member in every engineering department will claim that his/her field is the broadest engineering discipline, in the case of Mechanical Engineering that's actually true (I claim) because the core material permeates all engineering systems (fluid mechanics, solid mechanics, heat transfer, control systems, etc.)

Mechanical engineering is one of the oldest engineering fields (though perhaps Civil Engineering is even older) but in the past 20 years has undergone a rather remarkable transformation as a result of a number of new technological developments including

• **Computer Aided Design (CAD).** The average non-technical person probably thinks that mechanical engineers sit in front of a drafting table drawing blueprints for devices having nuts, bolts, shafts, gears, bearings, levers, etc. While that image was somewhat true 100 years ago, today the drafting-board has long since been replaced by CAD software, which enables a part to be constructed and tested virtually before any physical object is manufactured.

• **Simulation.** CAD allows not only sizing and checking for fit and interferences, but the resulting virtual parts are tested structurally, thermally, electrically, aerodynamically, etc. and modified as necessary before committing to manufacturing.

• **Sensor and actuators.** Nowadays even common consumer products such as automobiles have dozens of sensors to measure temperatures, pressures, flow rates, linear and rotational speeds, etc. These sensors are used not only to monitor the health and performance of the device, but also as inputs to a microcontroller. The microcontroller in turn commands actuators that adjust flow rates (e.g. of fuel into an engine), timings (e.g. of spark ignition), positions (e.g. of valves), etc.

• **3D printing.** Traditional "subtractive manufacturing" consisted of starting with a block or casting of material and removing material by drilling, milling, grinding, etc. The shapes that can be created in this way are limited compared to modern "additive manufacturing" or "3D printing" in which a structure is built in layers. Just as CAD + simulation has led to a new way of designing systems, 3D printing has led to a new way of creating prototypes and in limited cases, full-scale production.

• **Collaboration with other fields.** Historically, a nuts-and-bolts device such as an automobile was designed almost exclusively by mechanical engineers. Modern vehicles have vast electrical and electronic systems, safety systems (e.g. air bags, seat restraints), specialized batteries (in the case of hybrids or electric vehicles), etc., which require design contributions from electrical,

biomechanical and chemical engineers, respectively. It is essential that a modern mechanical engineer be able to understand and accommodate the requirements imposed on the system by non-mechanical considerations.

These radical changes in what mechanical engineers do compared to a relatively short time ago makes the field both challenging and exciting.

### Mechanical Engineering curriculum

In almost any accredited Mechanical Engineering program, the following courses are required:

- Basic sciences - math, chemistry, physics
- Breadth or distribution (called “General Education” at USC)
- Computer graphics and computer aided design (CAD)
- Experimental engineering & instrumentation
- Mechanical design - nuts, bolts, gears, welds
- Computational methods - converting continuous mathematical equations into discrete equations solved by a computer
- Core “engineering science”
  - Dynamics – essentially  $F = ma$  applied to many types of systems
  - Strength and properties of materials
  - Fluid mechanics
  - Thermodynamics
  - Heat transfer
  - Control systems
- Senior “capstone” design project

Additionally you may participate in non-credit “enrichment” activities such as undergraduate research, undergraduate student paper competitions in ASME (American Society of Mechanical Engineers, the primary professional society for mechanical engineers), the Formula SAE racecar project, etc.

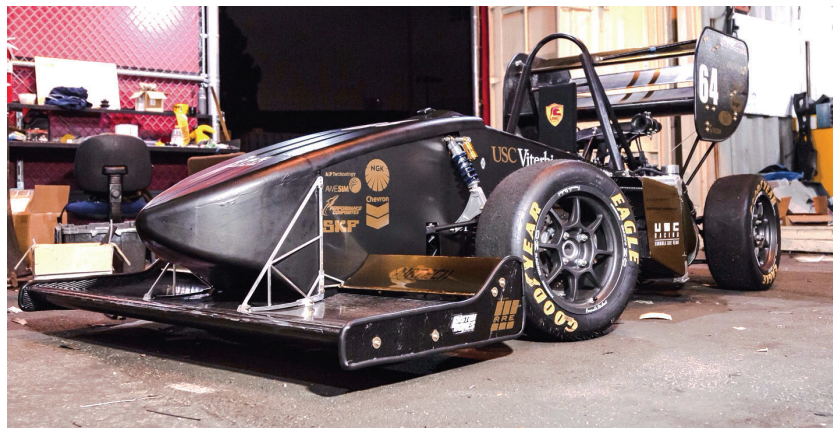


Figure 1. SAE Formula racecar project at USC (photo: <http://www.uscformulasae.com>)

## Examples of industries employing MEs

Many industries employ mechanical engineers; a few industries and the type of systems MEs design are listed below.

- Automotive
  - Combustion *احتراق*
  - Engines, transmissions *دستال*
  - Suspensions *تعليق*
- Aerospace (w/ aerospace engineers)
  - Control systems
  - Heat transfer in turbines
  - Fluid mechanics (internal & external)
- Biomedical (w/ physicians)
  - Biomechanics – prosthesis *پروتز*
  - Flow and transport in vivo
- Computers (w/ computer engineers)
  - Heat transfer
  - Packaging of components & systems
- Construction (w/ civil engineers)
  - Heating, ventilation, air conditioning (HVAC)
  - Stress analysis *تحليل توتس*
- Electrical power generation (w/ electrical engineers)
  - Steam power cycles - heat and work *دوران بخار*
  - Mechanical design of turbines, generators, ... *توليد*
- Petrochemicals (w/ chemical, petroleum engineers)
  - Oil drilling - stress, fluid flow, structures
  - Design of refineries - piping, pressure vessels *مخازن نفت*
- Robotics (w/ electrical engineers)
  - Mechanical design of actuators, sensors *مخازن نفت*
  - Stress analysis *تحليل توتس*

*in vivo* در موجود زنده  
*in vitro* به فرار از آزمایشگاه

*گرایش، تخصص، زمینه، طبع*